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14. ABSTRACT
We studied the growth, structural and magnetic properties of the hexagonal ferrite (BaAlxFe12-xO19) films on a surface of Pt template/Si wafer. We determine that our hexagonal ferrite films are highly textured, with the c axis perpendicular to the Si wafer surface and that Al substitution substantially increases uniaxial magnetic anisotropy from 17 to 25 kOe for x=0 and x=2 respectively. This increases in anisotropy field is governed by preferential substitution of Al ions into the 12k, 2a and 2b Fe sites as determined by our Mossbauer spectroscopy studies, consequently reducing magnetization. As a result, the ferromagnetic resonance frequency increases from 35 to 70

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Zbigniew Celinski
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Report Title

Final Report: Non-reciprocal on-wafer microwave devices

ABSTRACT

We studied the growth, structural and magnetic properties of the hexagonal ferrite (BaAlxFe12-xO19) films on a surface of Pt template/Si wafer. We determine that our hexagonal ferrite films are highly textured, with the c axis perpendicular to the Si wafer surface and that Al substitution substantially increases uniaxial magnetic anisotropy from 17 to 25 kOe for x=0 and x=2 respectively. This increases in anisotropy field is governed by preferential substitution of Al ions into the 12k, 2a and 2b Fe sites as determined by our Mossbauer spectroscopy studies, consequently reducing magnetization. As a result, the ferromagnetic resonance frequency increases from 35 to 70 GHz in zero applied field. We built a prototype of a fully integrated on-wafer, magnetically tunable band-stop filter on a Si substrate. The filter uses a barium hexagonal ferrite film incorporated into the dielectric layer of a microstrip transmission line. The zero-field operational frequency is about 34 GHz, increasing linearly with the strength of an applied magnetic field at a rate of about 2.7 GHz/kOe. Experimentally, high signal attenuation (33–67 dB/cm) at the resonance frequency and insertion losses as low as 4.5 dB were simultaneously observed, while the 3 dB device bandwidths were below 1 GHz.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
01/10/2013	8.00	Bijoy K. Kuanr, V. Veerakumar, Alka V. Kuanr, Kiran Lingam, S. R. Mishra, R. E. Camley, Z. Celinski. High frequency study of core-shell and uncoated Fe3O4 nanoparticles, Journal of Applied Physics, (02 2012): 7542. doi:
01/10/2013	6.00	Bijoy K. Kuanr, T. J. Fal, Z. Celinski, R. E. Camley. Iron based microstrip phase shifter; optimization of phase shift, Journal of Applied Physics, (02 2012): 7508. doi:
01/11/2013	9.00	T. J. Fal, R. E. Camley. Non-reciprocal devices using attenuated total reflection and thin filmmagnetic layered structures, Journal of Applied Physics, (09 2012): 53912. doi:
01/11/2013	11.00	Ian Harward, Yan Nie, Daming Chen, Josh Baptist, Justin M. Shaw, Eva Jakubisová Lišková, Štefan Viš?ovský, Petr Široký, Michal Les?ák, Jaromir Pištora, Zbigniew Celinski. Physical properties of Al doped Ba hexagonal ferrite thin films., Journal of Applied Physics (accepted for publication), (03 2013): 0. doi:
01/21/2013	12.00	Ian Harward, Yan Nie, Daming Chen, Josh Baptist, Justin M. Shaw, Eva Liskova, Stefan Visnovsky, Petr Siroky, Michal Lesnak, Jaromir Pistora, Zbigniew Celinski. Physical properties of Al doped Ba hexagonal ferrite thin films., Journal of Applied Physics (accepted for publication), (02 2013): 0. doi:
04/03/2014	13.00	E. Lišková-Jakubisová, Š. Viš?ovský, P. Široký, D. Hrabovský, J. Pištora, I. Harward, Z. Celinski. AlN/Fe/AlN nanostructures for magnetooptic magnetometry, Journal of Applied Physics, (05 2014): 0. doi: 10.1063/1.4868490
04/03/2014	14.00	Daming Chen, Ian Harward, Katie Linderman, Evangelos Economou, Yan Nie, Zbigniew Celinski. Properties of ferroelectric/ferromagnetic thin film heterostructures, Journal of Applied Physics, (05 2014): 0. doi: 10.1063/1.4865316
04/03/2014	15.00	Bijoy K. Kuanr, R. E. Camley, Z. Celinski, Adam McClure, Yves Idzerda. Single crystal Fe1-xGax thin films for monolithic microwave devices, Journal of Applied Physics, (05 2014): 0. doi: 10.1063/1.4864741
04/03/2014	17.00	K. Livesey, J. Ding, N. Anderson, R. Camley, A. Adeyeye, M. Kostylev, S. Samarin. Resonant frequencies of a binary magnetic nanowire, Physical Review B, (02 2013): 0. doi: 10.1103/PhysRevB.87.064424
05/26/2015	20.00	Nicholas R. Anderson, Zbigniew Jan Celinski, Robert E. Camley, Bijoy K. Kuanr. Monolithic Microwave Nonlinear Phase Shifter, IEEE Magnetics Letters, (2015): 0. doi: 10.1109/LMAG.2015.2406295
05/26/2015	22.00	E. Jakubisová, Š. Viš?ovský, P. Široký, D. Hrabovský, J. Pištora, I. Vávra, E. Dobro?ka, P. Kriš?an, H. Št?pánková, I. Harward, Z. Celinski. Magneto-optical studies of BaFe_12O_19 films grown by metallo-organic decomposition, Optical Materials Express, (05 2015): 0. doi: 10.1364/OME.5.001323

05/26/2015 21.00 M. Przybylski, J. ?ukrowski, I. Harward, Z. Celi?ski. Mössbauer spectroscopy study of Al distribution in BaAlxFe12?xO19 thin films,
Journal of Applied Physics, (05 2015): 0. doi: 10.1063/1.4914359

05/26/2015 19.00 R. E. Camley, Z. Celinski, I. Harward. On-wafer magnetically tunable millimeter wave notch filter using M-phase Ba hexagonal ferrite/Pt thin films on Si,
Applied Physics Letters, (10 2014): 0. doi: 10.1063/1.4900519

08/24/2011 1.00 Yuri Khivintsev,┐ J. Marsh, V. Zagorodnii,┐ I. Harward, J. Lovejoy, P. Krivosik,, R. E. Camley, and Z. Celinski. Nonlinear amplification and mixing of spin waves in a microstrip geometrywith metallic ferromagnets,
Applied Physics Letters, (01 2011): 42505. doi:

08/24/2011 2.00 Zihui Wang,, Young-Yeal Song,, Yiyan Sun,, Joshua Bevivino,, Mingzhong Wu,, V. Veerakumar,, Timothy J. Fal,, Robert E. Camley. Millimeter wave phase shifter based on ferromagnetic resonancein a hexagonal barium ferrite thin film,
Applied Physics Letters, (08 2010): 72509. doi:

08/24/2011 3.00 Yu. Garbovskiy,, L. Reisman,, Z. Celinski, , R. E. Camley,, A. Glushchenko. Metallic surfaces as alignment layers for nondisplay applicationsof liquid crystals,
Applied Physics Letters, (02 2011): 73301. doi:

TOTAL: 16

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

01/10/2013 7.00 I. Harward, Yan Nie, A. Gardner, L. Reisman,, Z. Celinski. Al doped Ba hexaferrite (BaAlxFe12-xO19) thin films on Pt using metalloorganicdecomposition,
Journal of Applied Physics, (02 2012): 7514. doi:

01/10/2013 5.00 I. Harward, T. O'Keevan , A. Hutchison, V. Zagorodnii, Z. Celinski. A broadband ferromagnetic resonance spectrometer to measure thinfilms up to 70 GHz,
Review of Scientific Instruments, (09 2011): 0. doi:

01/11/2013 10.00 N. R. Anderson, R. E. Camley. Attenuated total reflection study of bulk and surface polaritons inantiferromagnets and hexagonal ferrites: Propagation at arbitrary angles,
Journal of Applied Physics, (01 2013): 13904. doi:

04/03/2014 18.00 Yan Nie, R. E. Camley, Ying Wang. High-frequency nonreciprocal reflection from magnetic films with overlayers,
JOURNAL Od Applied Physics, (11 2013): 183908. doi:

TOTAL: 4

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Zbigniew Celinski, New Semiconductors and Devices Workshop, Northrop-Grumman, Los Angeles, December 11-12th 2014

Number of Presentations: 1.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Nanoparticle-Enhanced Liquid Crystal Radio Frequency Phase Shifter, U.S. Pat. App. No. 13/296,181 (still is being processed)

Metallic surfaces as alignment layers for non-display applications of liquid crystals

Patents Awarded

Metallic surfaces as alignment layers for nondisplay applications of liquid crystals - US 20130208194 A1 Application number US 13/766,615 Publication date Aug 15, 2013 Filing date Feb 13, 2013

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Ian Harward	1.00	
Nick Anderson	0.50	
FTE Equivalent:	**1.50**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Ian Harward	1.00
FTE Equivalent:	**1.00**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Zbigniew Celinski	0.08	
Robert E. Camley	0.08	
FTE Equivalent:	**0.16**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Jason Nobles	0.25	
FTE Equivalent:	**0.25**	
Total Number:	**1**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 1.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 1.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 1.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 1.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:..... 1.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Ian Harward
Total Number: 1

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

During the last year of this project our work concentrated in two areas:
1) Mossbauer studies of the Al doped BaAlxFe12-xO19 films and XRD studies of the bulk hexagonal ferrites to understand the nature of the Al substitution into the Fe sites
2) Development of fully integrated on-wafer band-stop filter using hexagonal ferrites films grown on Si wafer
3)
In addition we prepared a paper on a nonlinear phase shifter and another paper on magneto-optical properties of the hexagonal ferrite films.

Our work on materials for on-wafer microwave devices concentrated on barium hexagonal ferrite (BaM) films grown on Si because these material is a good candidate material for new generations of on-wafer microwave devices operating at frequencies above 40 GHz. Doping BaM with Al increases the value of anisotropy field significantly, and in combination with a large value of remanence, could allow one to create a self-biasing material/structure that would eliminate the need for permanent bias magnets in millimeter wave devices. To examine the occupation of Fe sub-lattices by Al ions, we carried out Conversion Electron Mossbauer Spectroscopy (CEMS) measurements at room temperature and zero magnetic field (after magnetizing the samples in a strong magnetic field). The spectra can be reasonably fitted with three components (sub-spectra) corresponding to different Fe sublattices. There are significant changes in the spectra with the addition of Al: The magnetic hyperfine field decreases for all three components, and their relative contributions also change remarkably. These observations are in agreement with the fact that the Al substitutes Fe, thus lowering the component contributions and the value of the hyperfine field. Specifically, the Fe sites 12k, 2a and 2b are preferentially occupied by the Al ions. As a result the saturation magnetization decreases significantly with Al doping and this decreases of the saturation magnetization is responsible for the significant increase of uniaxial anisotropy field. In addition, our previous XRD analysis indicates increasing grain misalignment with Al content, further supporting the CEMS data

We have devoted a significant effort to built a prototype of a fully integrated on-wafer, magnetically tunable band-stop filter operating at millimeter wave frequencies on a Si substrate. In contrast to earlier studies, our filter uses a very thin barium hexagonal ferrite film incorporated into the dielectric layer of a microstrip transmission line to filter the signal. We have used barium hexagonal ferrite film without Al doping, however the procedure to built would be identical using BaAlxFe12-xO19 films. The device operates by absorbing signals at the FMR frequency of BaM, while signals at off-resonance frequencies propagate through the structure with far less damping. The zero-field operational frequency is about 34GHz, increasing linearly with the strength of a static, perpendicularly applied magnetic field at a rate of about2.7GHz/kOe. Experimentally, high signal attenuation (33–67 dB/cm) at the resonance frequency and insertion losses as low as 4.5 dB were simultaneously observed, while the 3 dB device band-widths were generally below 1GHz. Our calculations are in quantitative agreement with the experimental results. We also find an important result that the thickness and conductivity of the Pt ground plane plays a key role in insertion losses, indicating directions for further improvements.

Technology Transfer